

Data Analysis and Quality Control for Main Injector Production Quadrupoles

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1 Introduction

This document describes the data analysis procedure used to produce “final” strengths and harmonics for Main Injector quadrupole magnets, and we also describe the quality control (QC) procedures for assessing these results. With some modification, these procedures are also useful for analyzing harmonics data on sextupole magnets.

2 Measurements

The Main Injector will require 34 100” quads (IQC-series) and 51 116” quads (IQD-series). These will be new magnets. In addition, we will measure some number of recycled Main Ring 84” quads (IQB-series) and 52” quads (IQA-series). The required production measurements on all of these magnets will be similar, and will consist of measuring the integrated gradient strength ($\int gdl$) as a function of current, and measurements of the harmonics at a number of currents.

The new IQC and IQD-series magnets will have a trim coil. There is an interest in measuring the change in strength as a function of trim coil current, but the measurement plan has not yet been worked out.

Another possible production measurement is the determination of the magnetic center with respect to the geometric center of the quads. As of this

writing, the necessity of performing this measurement on a routine basis has not been decided.

2.1 Measurement Probes

The primary measurement system is the MTF “HARMONICS” system using a Morgan coil. The standard coil to be used for production measurements is 126.5” in length (although by tradition it is called an eleven foot probe), which permits integrated strength measurements using one probe position for even the longest (IQD) magnets. The coils on the probe are: two dipole coils (2P1 and 2P2), two quadrupole coils (4P1 and 4P2), and the following higher-harmonic coils: 6P, 8P, 10P, 12P, and 20P.

Data will be acquired using the Unix-based “CHISOX” system; fluxes will be converted using a Metrolab PDI; and the data will be stored in Sybase.

The secondary measurement system will be a stretched-wire probe. It will be used to confirm the strength measurement and to measure the transverse gradient shape. This system is currently under development.

An alternative to the Morgan coil system is to build a tangential probe. This would have several advantages, including reducing data acquisition time. This probe has not yet been implemented.

2.2 Morgan Coil Test Plan

We will measure the harmonics at a number of currents. These currents now include:

up-ramp currents: 200, 425, 1000, 1575, 2000, 3000, 4000

down-ramp currents: 3000, 2000, 1000, 200, 0

The ramp is performed over a hysteresis loop having 4000 A maximum current and zero A minimum current. The number of currents can be changed without having to modify the analysis in any substantial way.

At each current, the strength is measured using the 4P1 coil. Harmonics are measured by rotating in turn each of the other coils, and finally repeating the rotation of the 4P1 coil as a harmonics measurement. Details of the reduction of rotating coil fluxes to harmonic coefficients is found in [1].

3 Data Analysis

The harmonic amplitudes in the “harmonics.harmonics_red_pnts” table are normalized to the probe radius; we wish to convert these to a standard radius, which is chosen to be 1 inch (2.54 cm). This is done by scaling the amplitudes according to

$$c_j = c_j(r_p) \cdot \left(\frac{r_0}{r_p}\right)^{j-2} \quad (1)$$

where r_p is the probe radius and the harmonic index j follows the convention $j = 1$ for dipole, 2 for quadrupole. The next step is to select the appropriate “good” harmonics from the collection of Morgan coils to form a set of harmonic coefficients for each current. A Morgan coil of order m (having $2m$ turns) is sensitive to the odd harmonics $j = (2n - 1)m$, for $n = 1, 2, 3, \dots$.

A table of the good harmonics for the coils in the standard MTF quad Morgan probe is listed in Table 1. In the table, the harmonics in **boldface** are the ones chosen to be put into the “good” list. The higher-order harmonics from the 2P and 4P coils are not very reliable, as shown from experience, and are not used, even in cases where they are the only source of a particular harmonic (e.g., the 14-pole). The 30-pole ($j = 15$) is a special case, in that it is available from two different coils (6P and 10P). There are several choices one can make; what we will implement is to write the 30-pole harmonic from the 10P coil into our “good” list and use the difference of the 6P and 10P measurements as a QC check. Finally, we note that the harmonics listed in the last row of the table are simply not available from any of our Morgan coils.

3.1 Recentering

Production measurements will be made with the Morgan coil placed nominally along the magnetic center of the quad. The 11' probe has a center bearing which rests on the “star tube” (the true beam tube is inserted after measurements). The purpose of this bearing is to prevent the probe from sagging; unsupported, the probe sags by about 0.11”. There is little if any way to adjust the probe center in x and y . This shouldn't matter, however, as long as the probe axis is near (within $\sim 0.10''$) the magnetic center.

<i>coil</i>	<i>m</i>	<i>“measured” harmonics</i>
2Pn	1	1, 3, 5, 7, 9, ...
4Pn	2	2, 6, 10, 14, 18, ...
6P	3	3, 9, 15, ...
8P	4	4, 12, 20, ...
10P	5	5, 15, ...
12P	6	6, 18, ...
20P	10	10, 30, ...
N/A		8, 16, ...

Table 1: Quad Morgan coils and their allowed harmonics.

We have shown that we can successfully correct the harmonics by using the reported dipole signal to calculate the displacement from magnetic center. This displacement is given by

$$\begin{aligned} x_0 &= -b_1 \\ y_0 &= -a_1 \end{aligned} \tag{2}$$

where a_1 and b_1 are the measured skew and normal dipole components, respectively, at 1” reference radius. Note that we get the dipole components measured twice, once by the 2P1 and also by the 2P2 coils, so we could take the average (and use the difference of the two measurements as an internal consistency check).

The recentering algorithm is done according to the well known “feed down” mechanism. That is, the harmonic coefficient of order j is changed by a summation over all higher order harmonics:

$$c'_j = c_j + \sum_{m=j+1}^{\infty} \binom{m-1}{j-1} c_m z_0^{m-j} \tag{3}$$

where the displacement $z_0 = x_0 + iy_0$ and the complex harmonic coefficients are $c_j = b_j + ia_j$. In practical terms, we note that since the positioning of the probe is generally within 0.050” of the magnetic center, the summation quickly converges. One problem is that there is no measurement of 16-pole, and if it is large (e.g., a feeddown test using large off-center displacements on

BQA019 estimate $b_8 = 1.6$ units), one may incorrectly estimate the correction for the 12-pole. However, the recentering is probably better than making no correction.

There are instances in which one intentionally places the probe axis far from the magnetic center. In this case, applying the recentering procedure is inappropriate and it is bypassed.

3.2 Combining measurements for short probes

We anticipate writing only full-length harmonics to the “results” tables (i.e., integrated over the length of the magnet). However, there may be instances where the 11’ probe is not available, in which case as a backup system we can measure the 100” and 116” quads with the 94” probe in two setups, with each setup measuring half the length of the magnet. In this case, one would combine the two measurements to get a weighted average for each harmonic.

3.3 Results database

The results of the harmonics measurements are written to the “results” data tables [4]. Reference run data are reported in table “results.magnet_harmonics” and the harmonic coefficients themselves are written to “results.magnet_harmonic_values.” QC checks will be performed against quantities stored in the “results” database using criteria stored

4 Quality Control Analysis

This section describes the various quality control (QC) parameters used in assessing the measurements of MI quads. The numbers contained in these tables will be stored in Sybase in the “quality_control” virtual database. The numbers stored in the tables will initially be “nominal” values; guidelines for updating these parameters are also given here.

The present version of this document describes parameters associated with rotating Morgan coil harmonics data. As other measurement systems (e.g., stretched wire) become integrated into the production testing program, their associated parameters will also be described here.

4.1 Types of parameters

The parameters which will be checked against QC criteria include the following classes:

- normal and skew harmonics (b_n, a_n): These parameters give us information about the quality of the magnet. The performance of the style of Morgan coil used at MTF leads to certain harmonic coefficients being measured with reasonable precision, but not others. Table 1 lists those harmonics for which we can expect to obtain useful measurements. We will compare these harmonics at certain selected currents against QC criteria, and ignore the others. The harmonics data will be obtained from the “results” virtual database; that is, they are the final processed values written by the analysis program.
- strength: This is the reference amplitude obtained from a 4P coil. We will compare this at several currents against QC criteria. The strength also gives us an important indication of the magnet quality..
- miscellaneous: The harmonics analysis program will calculate a number of subsidiary parameters which are usually associated with understanding the quality of the measurement, but may also be influenced by problems with the magnet construction. These miscellaneous parameters include at least the following (more may be added):
 - recentering parameters (x_0, y_0): most measurements on quads are made nominally at magnet center. These parameters use the measured dipole harmonics (b_1, a_1) to determine the displacement of the Morgan coil from center. A large value for x_0 or y_0 could indicate either probe misplacement or a serious magnet construction problem.
 - reference phase, offset angle: For “normal” style quads (IQC/IQD series), the reference phase should be 0, and the offset angle (calculated by the reduction program) should be close to some nominal value. Unusual values for these parameters usually indicate measurement setup problems (signal polarity reversal, power connected wrong) or probe slippage.

- noise estimates: the harmonics reduction will calculate various parameters based on fitting the FFT coefficients. These parameters will be useful for assessing the measuring quality, but will have little or no impact on determining the quality of the magnet.

4.2 QC limits

Each of the parameters described above will be compared with two levels of limits called Level 1 and Level 2. These levels are intended to indicate different levels of severity of discrepancy between measured values and nominal values.

Level 1 limits are generally set such that they indicate an “off-normal” condition in the magnet or measurement; they are typically set to be about 2 sigma away from the mean value of the parameter. For gaussian distributed data, Level 1 limits would be exceeded for about 5% of the measurement of the magnet, may be taken if enough QC parameters exceed their Level 1 limit. A single parameter being out of bounds may not, by itself, be cause for alarm.

Level 2 limits are set to indicate a serious out-of-tolerance condition, and are typically set at the 3-sigma distance away from the parameter’s mean value. For gaussian distributed data, Level 2 limits would only be exceeded in about 0.3% when things go wrong in the measurement process or in the construction of the magnet, the parameters are likely to have values be well beyond 3 sigma. A single QC parameter exceeding its Level 2 limit will be sufficient to call for a remeasurement.

For each level we define a low bound and a high bound according to the following scheme:

$$L2_low < L1_low < nominal_value < L1_hi < L2_hi$$

The database will store the 4 values `L1_low`, `L1_hi`, `L2_low`, and `L2_hi` associated with each QC parameter according to a scheme to be determined. It may also be useful to store `qc_par_mean` (mean value) and `qc_par_std_dev` (standard deviation) for each QC parameter based on the accumulated measurements for the magnet series. Note that we may wish to use separate QC parameter sets for each series (one for IQC’s and one for IQD’s), even though the harmonics should in principle be the same.

4.3 Currents

The harmonics are measured at 12 different currents between 0 and 4000 A. We could take the approach of setting separate QC limits at each of these currents; that is probably too many parameters to keep track of, and probably not productive, since most of the harmonics vary slowly with current. The behavior of b4 (the most critical of all the harmonics) is seen to have a natural breakpoint at ~ 1000 A — b4 falls typically by several units between 100 and 1000 A, and then rises slowly after that. A reasonable choice would be to select 100, 1000, and 4000 A on the upramp as the currents to be checked. Hysteresis leads to a different value of b4 on the downramp, with the difference being largest at 1000 A. The only other harmonic with a substantial current dependence is b6; the same set of currents would be sufficient to monitor its behavior. All of the other harmonics can probably be accommodated by determining, for each harmonic, its maximum and minimum values over the entire range of measured currents, and comparing those values against the QC limits.

References

- [1] H.D. Glass, “Measurement of Harmonic Amplitudes and Phases Using Rotating Coils,” MTF note MTF-94-004, 3/9/1994.
- [2] B.C. Brown, “Overview of the MTF Measurements Database,” MTF note MTF-92-0003.
- [3] author, “Design of the Harmonics Database,” ...
- [4] author, “Design of the Results Database,”